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THE MAGMATIC ALTERATION OF HORNBLLENDE
AND BIOTITE.

It is proposed in the following pages, which may be regarded as an elaboration of certain ideas expressed by me a few years ago, to discuss the causes of the well-known "magmatic alteration" or "resorption" of hornblende and biotite, and to suggest the possibility of certain consequences which seem to follow on this alteration¹ and which have an influence on the mineralogical composition of certain rocks.

The alteration of the two minerals in question to a granular mass of augite and magnetite is so well known to every petrographer, and such an excellent detailed description of it may be found in Zirkel's Lehrbuch (I, 716 ff.), that it is unnecessary to devote any space to a description of the facts. It must be recalled, however, that analogous alterations are extremely rare and of doubtful character in the pyroxenic minerals.

The important facts are also to be remembered that the chemical composition of both hornblende and biotite are structurally much more complex than that of the pyroxenes, and that they contain a greater variety of atoms, hydrogen and fluorine being very frequent, if not constant, constituents of both.

It must further be noted that augite is of all minerals one of the easiest to produce artificially either by dry igneous fusion or in other ways, and that melted hornblende invariably crystallizes, under laboratory conditions, as augite. Hornblende and

¹ The word *alteration* as used throughout this paper will be understood to mean only this "magmatic" alteration or "resorption."

biotite, on the contrary, have only been formed artificially in the most recent years. As far as the experiments go they seem to show that the presence of a mineralizing agent (a fluoride or silicofluoride) is necessary for the production of biotite in the dry way, while hornblende has been produced only in the wet way very recently by Chrustschoff. The negative evidence of the experiments points to the conclusion, that for the formation of either biotite or hornblende in an igneous magma pressure is a highly important if not necessary factor, while of no moment in the formation of augite.

CAUSE OF THE ALTERATION.

Current theories.—The theories in vogue to explain the alteration in question follow more or less closely Zirkel's¹ idea of a "caustic chemical action" of the magma on the hornblende and biotite crystals, and suppose either a fusion of the crystals, or their "resorption" (solution) by the surrounding magma and the subsequent crystallization of the augite out of the magma.

In regard to the magnetite there seems to be a difference of opinion, some supposing it to be not dissolved by the magma but crystallizing when the augitic constituents are withdrawn, while others seem to suppose it also to have been dissolved and recrystallized out of the magmatic solution.

These theories postulate an instability of the hornblende and biotite, or at least their instability as regards the solvent power of the magma surrounding them, under surface conditions.

While these various theories differ in details yet they may be discussed together, as the ideas involved in them are much the same and the objections to them are on the whole quite identical.

The current theories rest chiefly on the facts that the alteration proceeds from the outside inward and starts generally from crystal surfaces in contact with the magma; that the chemical composition of the magma has an apparent influence on the alteration, this being much less common in acid than in basic

¹ ZIRKEL *Mikroskop. Petrogr. U. S. G. Ex.*, 40th parallel, VI, 95, 1876.

rocks; that in the most glassy forms of the volcanic rocks the alteration is uncommon; and lastly that melted hornblende recrystallizes as augite.

These arguments are of great weight and will be discussed at greater length later on. Leaving them aside for the present, I would call the reader's attention to a fact often observed which they not only fail to explain but with which they seem to be quite at variance. This is the preservation of the original form of the hornblende or biotite crystal, with its sharp angles and straight edges, in a magma which has been in motion around it, as is shown by the flow structure and fragmentary hornblendes with their fracture surfaces unaltered. That the molten or dissolved zone surrounding the crystal demanded by these theories could possess sufficient cohesion or solidity to preserve its exact original form, unchanged by the, in many cases, powerful disrupting action of the moving magma, is to me quite inconceivable and passes the bounds of reasonable conjecture. Such a zone must be, in the nature of the case, more or less fluid, often as fluid as the surrounding magma, and hence easily subject to all kinds of distortion and disruption by the current. Yet such distortions as are expected are not found. In many cases the exact original form is preserved, and in the cases where the original form is lost the outlines are merely rounded by the removal of the outer portion, and the greater part, or the whole, of the remaining mass is composed of the granular alteration products.

The supposed fusion of the crystals has been accounted for¹ by the rise in temperature of the rock-mass on solidification which is demanded by theory and which has been actually observed.² But it has not been shown that the rise in temperature is sufficient for the fusion, nor why such an effect does not take place on the augites, which would destroy any zonal or hour-glass structure. Furthermore this hypothesis cannot explain the very numerous cases of alteration which took place while the

¹ LAGORIO, *Natur d. Glasbasis*, Min. Pet. Mitth. VIII, 463, 1887.

² ROTH, *Der Vesuv.*, Berlin, 1857, 304.

mass was in motion, and hence before solidification—an objection which is fatal.

That resorption of the hornblende or biotite substance may, and does, take place is not to be denied. The occurrence of hornblende and biotite crystals with embayments and irregular outlines, but with no alteration border, shows that here the resorbed substance has been carried off. These cases are exactly analogous to the corrosion phenomena seen in other minerals. It is indeed hard to explain why hornblende and biotite alone should be so favored as to have their substance and form left to them in the majority of cases, while quartz, feldspar, olivine and augite should lose part of their substance on corrosion so that we do not meet with a zone of different composition from their crystals or the groundmass.

The ægirine mantles about many quartzes in the basic rocks may occur to the reader as an exception. But this exception is apparent only because the two cases differ radically in kind. In the case of hornblende the change takes place within the original crystal space and is not due to a chemical combination of hornblende and groundmass substances; while in the case of quartz the change takes place outside the crystal in the groundmass and is essentially in the nature of a chemical reaction between the quartz and some of the molecules of the groundmass.

As a further objection may be mentioned the fact that, while the alteration in general starts from surfaces in contact with the magma, yet in some cases it is seen to proceed along cracks which, as far as can be seen, are untouched by it. The first objection made is, however, so difficult of explanation that it is perhaps needless to bring up more.

And after all, when we come to examine the current theories we find them rather vague and unsatisfactory. It is easy to dismiss the subject with the explanation that resorption of the hornblende and subsequent recrystallization of its substance as augite and magnetite has taken place, but it is difficult to realize how such a process takes place in actual fact with the results that we see. It is hard to see why the original substance alone should

crystallize out of the magmatic solution and take on again its original outlines, or at least the crystallographic outlines of hornblende, with changed molecular and molar structure; while the magmatic solvent, much of which is also certainly capable of crystallization under the same conditions, abandons the hornblende and solidifies as groundmass crystals or basis.

On the "magmatic" hypothesis we should expect the frequent occurrence of glass basis or groundmass among the grains, an expectation in which we are universally disappointed. It is true that we find other minerals than the two principal ones among the alteration products, but their formation is easily understood on other grounds.

Conditions of alteration.—Let us now examine briefly the conditions under which the alteration does or does not take place; which may be broadly divided into two classes—chemical and physical.

The chemical conditions relate to the magma in which the crystals are formed and in which they float, and for reasons to be seen presently we shall confine ourselves in discussing them to the volcanic rocks.

On examining the whole range of volcanic rocks the most striking fact that we notice is that the alteration of hornblende and biotite is chiefly confined to the intermediate group—those with from 55 to 65 per cent. of silica—the trachytes, andesites, phonolites and tephrites (both leucitic and nephelinic). It is of comparatively rare occurrence in the two extreme groups, the acid and the basic rocks, though more frequent in the latter than in the former.

The alteration among intermediate rocks, especially the andesites, is so extremely common that it is the exception rather than the rule to find specimens which show no, or even very few, altered crystals. Among these rocks we expect beforehand to find a greater or less amount of alteration of the hornblende and biotite (excepting in a few structural types), and are seldom if ever disappointed in our expectations. Indeed in many regions¹ the

¹OEBBEKE, Phillipines. Neu. Jahrb., B. Bd. I, 460; SIEMIRADZKI, Ecuador, ditto, B.

altered crystals predominate largely over the unaltered ones, occasionally to the total or almost total disappearance of the latter.

When we come to the acid and basic rocks we find that, while in both the alteration is comparatively rare, yet that there is a radical difference in the cause of the rarity in the two cases. In the basic magmas there are large amounts of iron oxides, magnesia and lime which here crystallize as pyroxene and olivine rather than as hornblende and biotite, which only rarely occur. When these two do occur, however, as in the hornblende basalts, they are almost invariably altered, so that the rarity of the alteration in these rocks is due to the rarity of the alterable minerals.

The case is quite otherwise in the acid rocks, where the bivalent metals, always in small quantities, go to form hornblende and biotite, pyroxene being of rare and abnormal occurrence in the rhyolites. Yet, notwithstanding their comparative frequency, though in small amounts, the alteration of these minerals is very unusual, the biotite being only occasionally blackened on the edges, while the hornblende is seldom changed.

We find in fact that while the absolute number of altered crystals is greatest in the andesites, yet that the proportion of altered crystals of hornblende or biotite among all those present is greatest in the basalts, where it reaches nearly 100 per cent., and decreases gradually, through the various intermediate rocks to the rhyolites where it is almost zero.

The general facts show that the chemical composition of the magma is a factor in the alteration process, though the rôle it plays is a rather obscure one. That it is a causal factor, *i. e.*, that the relative basicity of the magma in the intermediate and basic rocks immediately induces the alteration, does not seem to be probable in the light of facts to be given further on. It seems to be rather modifying in its action, the alteration which would

Bd., IV, 213, 1886; BLAAS, Persia, Min. Pet. Mitth., III, 474, 1880; HATCH, Arequipa, ditto, VII, 208-360, 1886; RUDOLPH, Peru and Bolivia, ditto, IX, 294, 304, 1887; K. VOGELSANG, Eifel, Zeit. d. d. g. G., XLII, 13, 18, 1890; GROSSER, Siebengebirge, Min. Pet. Mitth., XIII, 77, 1892; G. H. WILLIAMS, Fernando Noronha, Am. J. Sci., XXXVII, 184, 1889.

otherwise go on being prevented by the acidity of the magma in the rhyolites and allied rocks.

Turning to the physical conditions involved we find the eruptive rocks divided into two great classes; the plutonic rocks being those which in general have solidified at a great depth and consequently slowly and under great pressure, while the volcanic rocks have solidified at, or near, the surface and hence more rapidly and under little pressure. We find on examination of eruptive rocks in general that the two classes show a marked difference in the condition of their hornblende and biotite crystals.

In the plutonic rocks the hornblende and biotite (which are among the oldest components) are almost invariably unaltered, the borders being as clear as the interior and not showing any opacity or granular augite opacite aggregate. It is evident from their fresh and clear appearance that since their formation no forces have come into play (atmospheric and dynamometamorphic action being left out of account), to change them from their original condition. This invariability of non-alteration in the plutonic rocks would be absolute (so far as my knowledge goes) were it not for two exceptions. Both of these are in nepheline syenite, one from Sierra di Monchique in Portugal,¹ and the other from Serra di Tinguá in Brazil.² These two rocks, it is well known, are connected with peculiar dike types, and the group in general presents peculiar features. These two exceptions cannot then invalidate the general law, deduced from very numerous and world-wide observations, that in the plutonic rocks the hornblende and biotite are unaltered.

This constancy of non-alteration is in striking contrast with the behavior of the two minerals in the volcanic rocks. In these the alteration is extremely common, quite the rule, in fact, among the intermediate and basic members, though comparatively rare in the latter, owing to rarity of hornblende and biotite, and only failing completely (or practically so) at the extreme acid end.

¹ V. WERVEKE, *Neu. Jahrb.*, 1880, II, 151.

² GRAEFF, *ditto*, 1887, II, 236, 242, 244.

In fact, the more we study the igneous rocks, the more we are impressed with the great differences that the two minerals show in the two classes, as well as with the invariability of this behavior. In the one class of rocks we find the alteration "noticeable by its absence," while in the other the tendency is the other way, and its frequency is what most strikes us.

I have emphasized these respective characters because their invariability, resting as it does on such a broad basis of observations, shows that they are facts of prime importance for the solution of the problem. When we come to look at the class of volcanic rocks more closely, we find differences in special cases which are fully as constant and, while at first sight seemingly at variance with the above observations, are seen on further study not to clash but to be an almost equally important means to our end.

While the statement that the alteration is almost constant in the volcanic rocks (except the rhyolites, etc.) is true of the great majority of structural types, yet it has often been observed¹ that in the more glassy modifications the alteration is less than in the more crystalline; so that, speaking broadly, the frequency and amount of alteration may be said to be in roughly inverse ratio to the amount of glass basis present. Hence the above remarks on the invariability of alteration do not hold good for the highly vitreous forms, the obsidians, tachylytes, etc., in which both the hornblende and biotite are as a rule unchanged. Exceptions are to be found, but they are so few that they cannot impair our confidence in the general law that alteration is roughly inversely proportional to the amount of glass basis present, or, *coeteris paribus*, to the rate of cooling.

We must conclude, then, adopting the method of concomitant variations, and the factor of composition of the magma being eliminated by the researches of Hague and Iddings² and others (except in the rhyolites, etc.), that the alteration of hornblende and biotite does not take place under conditions of great

¹ Cf ZIRKEL, *Lehrb.*, I. 723. ROSENBUSCH, *Mikr. Phys.*, I. 484. II. (1887) 659.

² Bull. 17, U. S. G. S., 1885.

pressure and slow cooling, while conditions of slight pressure and slow cooling are extremely favorable, and again very rapid cooling and little pressure are unfavorable. The last set of conditions shows that the operation requires time, the crystals remaining unchanged because solidification, or else cooling below a temperature necessary for a molecular change, took place before alteration had time to set in. Our final conclusion, then, is that a diminution of pressure, together with a high temperature continued for some time, are the conditions necessary for the alteration.

Theory proposed.—This statement of conditions is based on such a large body of observations by the best petrographers on all classes of igneous rocks and from such a great variety of localities, and the exceptions to it are so few, that it seems to me we can safely accept it in trying to frame a theory to account for the alterations. Such a statement, by showing us the conditions under which the phenomena in question occur, points the way toward their explanation. The explanation of the alteration now proposed rests at bottom on the chemical nature of hornblende and biotite.

As has been briefly noted on page 257, and as may be seen on reference to any mineralogical handbook, these two minerals are much more complex in their molecular structure than pyroxene, one of the consequences of this complexity being, as is also indicated by experiment, that great pressure is necessary for their formation in an igneous magma,¹ with probably the presence of certain mineralizing agents.² That the latter are present in the magma is indicated by the content of hydrogen and fluorine in them in greater or less amounts.

This idea as to the conditions of formation of the two minerals, which Siemiradzki³ was apparently the first to propose,

¹ The cases of uraltic hornblende and secondary biotite due to meteorological or dynamical agencies are not included in this statement. Only their formation in igneous magmas is referred to, and it is well known that a mineral may be formed in several quite different ways.

² Cf. LÉVY, *Structures des Roches Eruptives*. Paris, 1889, 90.

³ SIEMIRADZKI, *Neu. Jahrb. Bd. IV.* 307, 1886.

does not carry with it the implication that augite as well may not be formed under the same conditions (as Siemiradzki seems to suppose). On the contrary, many facts, such as the inclusion of augite in phenocrystic hornblende and the like, show conclusively that augite can be formed under the same conditions as hornblende.

It would be perhaps rash to say that under plutonic conditions the bivalent molecules tend to form hornblende and biotite rather than pyroxene, but a hint that this is the case is furnished by the general preponderance of these two minerals over pyroxene in the plutonic rocks. The predominance is not, certainly, as great as might be wished to establish this point clearly, but that it exists is quite evident on considering the much greater abundance of the hornblende and biotite bearing plutonic rocks over the augitic; the granites, hornblende and biotite syenites and diorites surpassing, both in quantity and in number of occurrences, their augitic varieties as well as the gabbros in the broader sense. This question, however, which has no especial bearing on the present hypothesis, is merely brought in parenthetically.¹

It is evident from their freedom from alteration in the plutonic rocks that hornblende and biotite are stable under plutonic conditions down to the last moment of solidification, while their constant alteration in the majority of volcanic rocks shows that they are unstable under diminished pressure, a fact that the experiments of Becker² and Doelter and Hussak³ tend to confirm.

This instability⁴ under conditions of high temperature and diminished pressure is due, according to my view, directly to

¹It may be mentioned that Brögger (*Gor. Ting. Serie, Krist.* 1895, 36) states that in the grorudites the hornblende evidently represents an older phase of crystallization than the ægirine.

²BECKER, *Neu. Jahr.*, 1883, II, 1 ff.

³DOELTER and HUSSAK, *ditto*, I, 1884, 23.

⁴ROSENBUSCH has already recognized this idea of instability, but without assigning a reason for it (*Mikr. Phys.*, II, 660, 1887). Cf. G. H. WILLIAMS, *Am. J. Sci.*, XXVIII, 259, 260, 1884.

the highly complex chemical character of hornblende and biotite. This is in accordance with the well-known chemical law that compounds are more unstable the greater their molecular weight and the more complex their molecular structure.

The theory here presented is that we must suppose the hornblende and biotite crystals to have been formed at an early (intratelluric) period under conditions of great pressure, and probably in the presence of mineralizing agents. As they are brought near the surface in the course of the eruption the pressure diminishes while the temperature remains high, till a point is reached where the substance is no longer stable. Here a molecular change is begun, inducing at the same time a molar change, so that the chemically and physically homogeneous mass of hornblende or biotite becomes a chemically and physically heterogeneous granular mass of augite and magnetite.

The formation of a mixture of diopside or augite and magnetite out of hornblende or biotite substance is easily conceivable and chemically quite possible, in the case of biotite lime being taken from the magma. Similar changes are not at all uncommon in the range of chemical mineralogy, and the resulting masses may be properly called paramorphs.¹ Perhaps the best analogous example is that of the change of leucite to so-called pseudo-leucite, a mixture of orthoclase and nepheline, as described by J. F. Williams.² In the case of hornblende, on this theory, the bulk analysis of the paramorph should be identical with that of the original mineral, or almost so (as is the case with pseudo-leucite). In the case of biotite which contains no lime (or, at least, only traces), that necessary for the formation of augite or diopside must be derived from the magma, while the potash of the biotite passes into this, or goes to form accessory feldspar. Such an interchange of atoms involves no theoretical difficulties, as similar ones are extremely common in cases of pseudomorphism and metamorphism. It may also be noted that the alteration of biotite produces larger

¹ ROTH, *Geologie*, I, 64.

² *Geol. Surv. Arkansas*, 1890, II, 268.

magnetite grains and less augite than that of hornblende,¹ which is quite in accordance with its greater content of iron and lack of lime. No chemical difficulties are encountered in the case of the accessory alteration products, hypersthene, olivine and feldspar, the molecules necessary for their formation being present in the mother mineral.

The process requires apparently considerable time, and we may suppose that it continues from the point where instability begins till the mass becomes solid. It is possible that it may continue for some time after solidification has set in, but of this we have no evidence. Whether the magma is in motion or at rest has no effect on the alteration process, though the effects produced by a moving magma on the alteration product may have important consequences, as we shall see.

The formation of augite may take place at the same time as the hornblende, but is not hindered by diminution of pressure, and may possibly be favored by it. So that augite may and does crystallize out of the magma, either as small groundmass crystals or microlites, or as zonal accretions around phenocrysts brought up from below, at the same time that the alteration of hornblende and biotite is going on, or even after this has ceased for lack of alterable material.

The relative chemical complexity explains satisfactorily the fact that analogous alterations are seldom, if ever, seen in either the monoclinic or orthorhombic pyroxenes, or in olivine, which are much less liable to change, owing to their comparatively simple composition and structure. This also explains the recrystallization of melted hornblende as augite.

It will be evident that this theory of simple molecular change involves no change of form such as would necessarily arise on fusion or solution of the crystal. The preservation of the original shape is in accordance with the facts of pseudomorphism, and it is easily conceivable that the fine grained product should possess in many cases sufficient cohesion between its closely packed and interlocked grains to resist considerable dis-

¹ ZIRKEL, *Lehrb.*, I, 721.

rupting force of a surrounding moving magma. In most cases, however, the mass will be somewhat incoherent, so that it will be broken up by the action of the current, yielding the rounded forms so generally observed, and leading to other consequences of importance.

It will also be seen that there is nothing in the theory incompatible with a true resorption or solution of the hornblende or biotite substance if it should be enveloped in a part of the magma in which it is soluble under the conditions prevailing. In this case, however, we would look for embayments and other true corrosion phenomena, with a disappearance of the dissolved substance, while the pseudomorphism process could go on at another, or the same, time.

It may seem, at first sight, that the starting of the alteration at the surface and its gradual progress inwards is a serious objection to this theory, in accordance with which we might think that the change should take place all at once through the whole crystal. But when we come to examine other cases of paramorphism such as the change of monoclinic to rhombic sulphur, or wrought to cast iron, we find that the changes here take place from certain definite points or surfaces (generally the latter), so that this uniform progress of alteration need not surprise us, especially in view of the fact that the alteration evidently requires time, as in all similar changes.

It is possible also that this method of progress is dependent on the hydrogen or fluorine content of the two minerals, the attraction between their molecules and those of the other constituents being lessened by diminished pressure at the temperature of the liquid magma, so that they tend to dissociate, thus causing a molecular disintegration and starting the molecular rearrangement. Such an action in their case would naturally start at the surface or along cracks, the walls of which need not be in actual contact with the magma. This action of the gaseous contents of the minerals would also explain the cases of non-alteration, in elsewhere altered crystals, where abutting against other phenocrysts.

The non-alteration in the very acid rocks is a fact which is difficult to explain by any of the hypotheses under consideration. Since the indications are that rhyolite when erupted is at a higher temperature than more basic rocks we could on the magmatic theories look for greater alteration in them than in the andesites or basalts. Since the reverse is the case their behavior militates rather against these theories. On the resorption theory proper we could also expect to find in the acid magmas a greater tendency towards solution of the ferromagnesian crystals, as is hinted at by Rosenbusch,¹ which we do not find. Glassy forms are extremely common in these rocks, and it is possible that the non-alteration is connected rather with this structural and physical peculiarity than with their chemical composition.

It is probably premature to discuss this question at present in view of the scantiness of our knowledge, so that we may merely assume that the large amount of SiO_2 , and perhaps K_2O , exerts some deterrent effect on the process of alteration, of the nature of which we are ignorant. It is possible that the non-alteration in rhyolites is connected with the tendency of acid magmas to form hornblende and biotite rather than augite. It may also be suggested here that the influence of the composition of the magma on the alteration process may be analogous to the influence of the nature of a solvent on the molecular condition of the dissolved substance.²

CONSEQUENCES OF THE ALTERATION.

Action of the magma.—Accepting the alteration and its attendant phenomena as facts we may examine some of the consequences of this change and see what light they throw upon a few petrological questions.

The disrupting action of the moving magma current on the granular aggregate has already been referred to, yielding the rounded forms so commonly seen. This simple mechanical action of the current would tend to scatter the augite and

¹ ROSENBUSCH, Mikr. Phys., II., 660, 1887.

² NERNST, Theoretical Chemistry. London and New York, 1895, 387.

magnetite grains through the groundmass, and the process may often be seen, so to speak, in operation, where a tail or streamer of such grains is observed proceeding from a rounded, altered crystal.

It is not to be supposed that these grains will be resorbed or dissolved by the magma under ordinary conditions. The presence of augite microlites and crystals which have been formed down to the last stage before solidification, and the accretions about augite phenocrysts, precludes any such idea for the augite. Iddings¹ has shown that where resorptive action takes place the last minerals to crystallize should be the first to be resorbed, so that the magnetite grains are also safe from the attack of the magmatic ogre. It follows, therefore, that, provided the mass be in sufficient motion, the greater the alteration of hornblende and biotite the greater will be the abundance of augite and magnetite grains in the groundmass.

This conclusion may be supported by numerous observations:

H. Vogelsang² was the first to suggest that the "opacite" grains in the groundmass were derived from altered hornblende and biotite crystals by mechanical disintegration.

Zirkel³ concludes that "many of the dark grains scattered through rocks are really the finely-distributed, powder-like particles of the pyrogenous alteration product of hornblende."

Mügge,⁴ in his paper on the rocks of the Azores, makes the definite statement that augite grains as well may have been derived from altered hornblende and biotite crystals. We have also the interesting fact shown that the augites which crystallize out of the magma may be, and are in this case, of a different composition. On page 224 he says that certain groundmass olivines "appear in these cases, as sometimes in trachytes elsewhere, to have been produced from hornblende and biotite by resorption (Umschmelzung)."

¹ IDDIGS, *Cryst. Ign. Rocks*, Bull. Phil. Soc., Washington, XI., 105, 1892.

² H. VOGELSANG, *Philosophie d. Geologie*, Bonn, 1867, 192, *cf.* also his *Die Krystalliten*, Bonn, 1875, 157.

³ ZIRKEL, *Mikr. Pet.* 40th Parallel, Washington, 1876, 95; also *Lehrb.*, I., 717.

⁴ MÜGGE, *Neu. Jahrb.*, 1883, II., 1895.

Von Lasaulx¹ concludes that the rock-magma of the augite andesites of Hemmerich in the Siebengebirge must have been much more rich in hornblende at an early stage, and that the preponderance of augite, as well as magnetite, could have come about through resorption (*Einschmelzung*) of the hornblende. Grosser,² in a later work on the same region, comes to the same conclusion.

Hatch³ notes a connection between the alteration of the hornblende and the presence of magnetite in the groundmass of certain Peruvian andesites, observing that in cases where the hornblende is "resorbed" magnetite is abundant, while in rocks where the mineral is unchanged the groundmass contains no magnetite grains. No definite mention of augite is made in this connection, but on page 359 he states that "hand in hand with the resorption of the hornblende goes an increase in pyroxene and magnetite."

Finally two examples drawn from my own experience may be given, one the hornblende basalts of Kula in Asia Minor,⁴ and the other the andesites of Ægina and Methana.⁵ In these the relation of the abundance of augite and magnetite grains in the groundmass to the alteration of the hornblende is well shown.

We see from these examples that in many andesites, as well as in other volcanic rocks, a part of the groundmass augites (and magnetites) have been derived from hornblende or biotite through alteration, whether "magmatic" or "molecular" it matters not.

It is possible that we have in this fact the explanation of the so frequent occurrence of imperfect grains of augite in the groundmass of many rocks. Augite and magnetite tend to be anomalous in this respect, as the groundmass crystals of the other rock-forming minerals—the feldspars, quartz, hornblende,

¹ VON LASAULX, Sitz. ber. Niederrh. Ges. in Bonn., XLI., 155, 1884.

² GROSSER, Min. Pet. Mitth., XIII., 77, 1892.

³ HATCH, Min. Pet. Mitth., VII., 347, 1886.

⁴ Am. J. Sci. LXVII, 121, 1894.

⁵ JOUR. OF GEOL., III, 21-46, 1895.

hypersthene, apatite and sphene—show comparatively few imperfect forms, and have a greater tendency toward definite crystallographic outlines. In augite, on the contrary, the groundmass crystals are often sharply divisible into imperfect grains and definite crystals.

Origin of some augite andesites.—By this idea of scattering of the granular alteration product of hornblende and biotite through the groundmass we are brought face to face with the question of the origin of many augite-andesites, and their classificatory separation from the hornblende and biotite-andesites. This problem has been touched upon by several writers and some discussion of it may be found in Zirkel's Lehrbuch (II, 817).

The separation of the augite from the hornblende-andesites has been opposed on the ground of the abundance of transition forms and the consequent difficulty of drawing a fast line between the two. Such an objection would however lie against almost any of the well established rock groups, and I fully concur with Rudolph^{*} in his opinion of the importance of well characterized types at each end of the series.

That the two main classes may be rationally separated in general on the grounds of different mineralogical composition, together with correlated chemical and structural variation, cannot be doubted very seriously at the present time. But the alteration of hornblende and biotite tends to complicate matters somewhat.

It must be stated here, and the fact must be insisted upon, that the hypersthene andesites in general, as Zirkel says, and many of the true augite-andesites are of an undoubtedly original character, *i. e.*, the component characteristic pyroxenes have crystallized normally out of the magma. On the other hand the facts of the alteration make it extremely probable that some of the augite-andesites are of a derivative character, *i. e.*, that their magmas were originally hornblendic or biotitic, but that these minerals have been replaced by augite and magnetite through the process of alteration and the consequences of the action of the moving magma on the products.

^{*} RUDOLPH, Min. Pet. Mitth., IX, 316, 1887.

This idea was first broached by Von Lasaulx,¹ and his remarks are of such importance that a full quotation of the passage bearing on this point may be given :

"A conclusion which follows directly from the observations on the character of the constituents of the andesites of the Siebengebirge is this, that the less hornblende a rock holds the more it approaches a true augite-andesite, and the more the hornblende shows signs of resorption, so much the richer is the groundmass in finely divided magnetite. If . . . the hornblende is a constituent which has separated out of the fluid magma as one of the earliest at a great depth, then it would depend on how far the originally formed hornblende had undergone fusion and solution whether a rock appears in the upper regions as hornblende-rich or hornblende-poor. That augite is formed out of the magma easily and abundantly through resorption of enclosures and the earliest crystals can likewise be shown by experience; on the other hand hornblende appears to have been formed in this manner much less often. Likewise the magnetite of the groundmass can be increased by refusion of small hornblende crystals.

"An augite-andesite can therefore arise out of an original probably hornblende-andesite magma, if this remains in a state of liquidity so long that the hornblende which has been formed at a depth may be again wholly, or mostly, dissolved, and augite and magnetite be formed in its place."

The general similarity of the views expressed in the above quotation as to the origin of some augite-andesites with my own is apparent. It must be remarked, however, that the conclusions are as true of biotite as of hornblende, and also that I differ radically from Von Lasaulx in considering that the derivative augites are not crystallized out of the magma from dissolved hornblende substance, but are due to a molecular change and subsequent mechanical disintegration.

Zirkel expresses himself as against such an origin, saying that it would apply in any case not to the phenocrystic but only

¹VON LASAULX, *op. cit.*, 1858.

to the groundmass augites, and further that it is unscientific to connect closely a hornblende-free augite-andesite with a hornblende-andesite because part of the augite of the former could have been possibly in the condition of hornblende at an earlier magmatic period.

While not wishing to be in any degree polemical I must differ in this matter from Professor Zirkel, as it seems to me to be an inevitable conclusion from the facts that many of the groundmass augites in certain andesites have been so derived from altered hornblende substances. Mügge's example of the Azores trachytes already cited shows also that such derivative grains may attain the size of phenocrysts and hence be reckoned as such, through accretion of crystallizing augitic substances. Such a derivative origin must not, however, be attributed to all phenocrysts nor to the well formed augite-microlites and groundmass crystals. Nor is such an attribution necessary, as I have already pointed out that hand in hand with the alteration of hornblende may go on the crystallization of augite out of the magma. It may be mentioned here that Zirkel¹ speaking of the hornblendes in pyroxene-andesites says that they give the impression that they had nothing to do with those conditions of solidification in which the rock-mass as it exists at present was produced, from which the inference is to be drawn that they have been formed at a much earlier period.

But when Zirkel brings the charge of being unscientific against the idea of the derivation of augite-andesites from hornblendic magmas, he touches upon what seems to me to be a vital and important point in the question. If it were sweepingly asserted that all, or even the most, of the augite-andesites were to be connected with hornblendic magmas² his reproach would be justified, as being an unwarranted and too broad a generalization from the facts. But if it can be shown that certain augite-andesites are of independent origin while others are derivative from a previously hornblendic magma, then we have advanced a step

¹ ZIRKEL, *Lehrb.* II, 811.

² As VON LASAULX perhaps seems to do.

in our knowledge of this group of rocks—a step which may lead to the extension of our knowledge in other directions. The question as to whether the knowledge of such an origin should affect the present classification is a question apart and need not be discussed here.

Acid augite-andesites.—A consideration of the phenomena already discussed, as well as others to be mentioned presently, has led me to the conclusion that, besides the normal augite-andesites which make up the greater part, such derivative augite-andesites do exist, in which a large part of the augite present is due to the alteration of hornblende. What the grounds are for this view I shall endeavor to show, though my remarks must be taken as suggestive of what may be the case, rather than as even approaching a full discussion of the subject.

It is quite well established that hornblende and biotite are the prevalent, or one might say favorite, ferro-magnesian silicates of the more acid rocks, though ægirine is abundant in acid phonolites and some trachytes, while augite is characteristic of the more basic rocks. This being so we could expect *a priori* to find the augite-andesites more basic than the hornblende or biotite-andesites. While this is the fact in many cases, yet exceptions are numerous, the abnormal acidity of many of the augite-andesites being remarked upon by Zirkel¹ and Rosenbusch,² as well as by others.

Some particular instances of the high acidity of augite-andesites occurring together with other andesites may be given. On the volcanic line in the Ægean Sea are found the two centers of Santorini, which has poured forth almost exclusively pyroxene-andesites, and Ægina-Methana, where hornblendic andesites and dacites are abundant as well as pyroxene andesites. I have elsewhere³ pointed out the similarity in the general magmas of the two centers, and yet when we come to examine the rocks of the two districts in reference to the present point we meet with a

¹ ZIRKEL, Lehrb. II, 802.

² ROSENBUSCH, Mik. Phys. II, 651-683, 1887.

³ JOUR. OF GEOL. III. 166, 1895.

somewhat striking result. In Ægina-Methana the analyses of the hornblende-andesite (excluding segregations) show an average silica percentage of 59.41, while at Santorini the pyroxene andesites are very acid, the silica average of the analyses quoted in the paper just cited, being 61.41 per cent., and the latest products of eruption range from 66.15 to 68.89.

Again we find in the Washoe District,¹ the Yellowstone Park,² Colombia,³ and Ecuador⁴ that eruption of the hornblende and pyroxene-andesites have taken place, and that many of the latter are as acid as, or more so than many, of the accompanying hornblende-andesites. Other instances of the abnormal acidity of augite-andesites that might be quoted are not rare, and the frequency of such occurrences is certainly surprising in view of what we might *à priori* expect.

In 1881 Gumbel⁵ pointed out that the andesites of the Andes could be referred to two types, which he called the trachytic and the basaltic, the former with over, and the latter with under, 57 per cent. of silica. Later, in 1883, Cross⁶ suggested that the augite-andesites may be divided into three groups; the "trachytic" with a high percentage of silica, the "basaltic" which are the most basic and pass into the true basalts, and the "intermediate" normal augite-andesites with a silica percentage of 56 to 60.

That the "intermediate" and "basaltic" augite-andesites have had the greater part at least of their augite crystallized out of the magma in a normal way, and hence that they are really augite-andesites in a true sense of the word, seems to be generally the fact; though cases might be brought up in which a derivative origin could be rightly attributed to a part of the augite even of these.

¹ HAGUE and IDDINGS, Bull. U. S. G. S. No. 17, p. 33. *cf.* also CROSS, Laccolite Mt. Groups, XIV, Rep. U. S. G. S. 227, 1895.

² IDDINGS, Electr. Peak, XII Rep. U. S. G. S., 627, 628, 1892.

³ KÜCH, Petr. vulk. Gest. Rep. Colombia, Berlin, 1892, 78, 79.

⁴ SIEMIRADZKI, op. cit., 205, 206.

⁵ GÜMBEL, Sitz. ber., Münch. Akad., XI, 365 ff., 1881.

⁶ CROSS, Bull. No. 1, U. S. G. S., 36, 37, 1883.

Leaving these aside, we may confine our attention to the acid, "trachytic," augite-andesites. In the magma of such a rock we could naturally expect the formation of hornblende or biotite rather than augite.

Zirkel¹ explains the high acidity by the abundant presence of a glass basis which is often much more acid than the rock itself, as shown by Lagorio's² analyses. This explanation, however, only shifts the difficulty one step back, or rather states it in another form, since Lagorio's analyses also show that in basalts³ the basis contains almost exactly as much silica as the rock.

The explanation which is suggested here is that these acid augite-andesites are derived from original hornblende or biotite-andesitic magmas. The magma came up with crystals of hornblende or biotite already formed, and these underwent alteration and disintegration as already described, while at the same time the rest of the ferro-magnesian molecules present in the magma crystallized as augite or hypersthene under the existing low pressure conditions.

Against this view may be brought a number of objections, one of those which most naturally occurs being that in the very acid rocks, as the rhyolites, the tendency is for the hornblende and biotite to remain unaltered. This objection is of weight, but it must be remembered that the acid andesites in question seldom, if ever, attain to the high acidity of the rhyolites, and further, that they are chemically quite different otherwise.

A detailed study of the various augitic andesites, and especially the more acid ones, would undoubtedly throw much light on the question and show which explanation (if either) was correct. Such a study would, however, carry us beyond the bounds of this article, and is, moreover, impracticable for me at present.

Variation with geological occurrence.—It is evident, from the facts of the alteration, that the physical conditions under which

¹ ZIRKEL, Lehrb. II, 819.

² LAGORIO, Min. Pet. Mitth., VIII, 458, 467, 1887.

³ LAGORIO, op. cit., 479.

the magma is erupted and consolidated would, to a certain extent, control the formation of augite on this hypothesis. We may therefore examine a few cases of variation of mineralogical composition with geological occurrence which seem to bear out the view that many acid augite-andesites (and some of the more basic ones) are derived from hornblende-andesitic magmas of normal composition.

In the andesites of the Auvergne, as recently described by Fouqué,¹ the hornblende and biotite crystals are generally altered in the effusive lava streams, while in the very glassy effusives and in the dike rocks (which, according to Fouqué, have cooled quickly) they are fresh and augite is rare. It may be noted here, *en passant*, that in these rocks the presence of dusty inclusions in the apatite crystals seems to go hand in hand with the hornblende.²

In the augite-andesite flows of Mount Cimino, Deecke³ observed that biotite predominates on the borders, while augite takes its place in the interior, of the streams.

The difference observed by Hazard⁴ in the stock and sheet basalts of the Lausitz is noteworthy. The latter are normal olivine basalts, with or without nepheline, while the former are hornblende basalts. His conclusions are that hornblende separated out as phenocrysts only in the eruptive canal, that it was gradually resorbed, changing into augitic substance, and that further on, when the rock spread out as a sheet, or was injected into cracks, olivine invariably separated out. "It is hence possible to judge of the nature of the occurrence of our basalts (whether sheet or stock) from the constituents."

The explanation of such occurrences on the theory here suggested is quite simple. Hornblende and biotite, which have been formed at a depth, are preserved intact when the

¹FOUQUÉ, L'Etude des Feldspaths, Paris, 1894, 193-270.

²Cf. BLAAS, Jung. Erupt. Gest. Persiens. Min. Pet. Mitth., III., 476 ff., 1880. Also, MERRILL, Erupt. Rocks fr. Montana. Proc. U. S. Nat. Mus., XVII., 642, 1895.

³DEECKE, Neu. Jahrb. B. Bd., VI., 231, 1889.

⁴HAZARD, Min. Pet. Mitth., XIV., 303 ff., 1894.

magma solidifies under sufficient pressure, as in the Lausitz stock; or where it cools so quickly that time is not given for alteration, as in the Auvergne dikes or the borders of the Mount Cimino streams. They undergo more or less alteration (and are hence replaced by augite) when such time is given them while they are simmering under slight pressure in the throat of the volcano, as seen in the lava flows of Auvergne and the Lausitz. In the case of the Mount Cimino flows we may suppose that the slow cooling of the interior under slight pressure gave opportunity for the replacement of the biotite by augite.

There are certain other cases where it seems possible that for some reason the magma was brought near the surface before the formation of hornblende or biotite had taken place to any extent, so that the crystallization of augite out of the magma took place, instead of either of the two other minerals.

As an illustration of this may be mentioned the volcanoes of Santorini. Here the highly acid pyroxene-andesites ejected by the later eruptions which formed the small island cones in the center of the bay show in the abundant glassy groundmass a large preponderance among the augites of well-formed prismatic micro-lites, as well as abundant hypersthene prisms, neither of which could be due to the alteration of hornblende, while augite grains are quite rare. The lava flows which go to make up the external crater ring of Thera and Therasia are in general much more crystalline and at the same time contain many more imperfect grains of augite, as I gather from examination of specimens collected by myself, and from some of Fouqué's remarks.¹ In this connection it is of interest to note that the hornblende crystals in the hornblende-andesites of Acrotiri very seldom show alteration phenomena.²

These explanations may seem forced or unnecessary to many, but they are only offered as suggestions of the applications of the idea of the instability of hornblende and biotite under eruptive conditions to certain problems of petrology. The forces

¹ Fouqué, Santorin, Paris, 1879, 291, *et al.*

² Fouqué, Santorin, 357.

involved in an eruption and the conditions under which the magma reaches the surface are probably so complex and certainly to so large an extent unknown to us that any explanation of such phenomena must be, after all, largely mere speculation at the present time.

Still it must be granted that the explanation of the above facts based on the process and consequences of alteration are within the bounds of reason, and our brief review points rather to than away from the conclusion that alteration of hornblende or biotite is responsible for a great part of the acid augite-andesites, as well as some of the more basic members of the group.

The foregoing remarks lead us directly to the consideration of another application of the ideas advanced in these pages to theoretical petrology, which may be briefly touched upon before closing this paper. I refer to the succession of erupted rocks at volcanic centers. In many places we find pyroxene-andesites among the later rocks following hornblende or biotite-andesites. Thus in the Eureka district the order of succession as given by Hague¹ is: hornblende-andesite, hornblende-biotite-andesite, dacite, rhyolite, pyroxene-andesite, and lastly basalt. Again at Sepulchre Mountain² the lower breccias are hornblende or biotite-andesites, while the upper and consequently later breccias are almost wholly of pyroxene-andesite. While recognizing the fact that the causes and circumstances involved are extremely various and complex, it may be suggested that such successions may be due in part to causes similar to those already spoken of in connection with the variation of mineralogical composition with geological occurrence; namely, that the hornblende or biotite of the original magma may have been replaced by augite during a period of liquidity under diminished pressure.

SUMMARY.

After a brief discussion of the current theories referring the alteration of hornblende and biotite to a resorptive action of the

¹ HAGUE, Geol. Eureka Distr., Mon. XX, U. S. G. S., 290, 1892.

² IDDINGS, op. cit., 634, 635.

magma and a statement of certain objections to them, the conditions under which the alteration does or does not take place are described and the conclusion arrived at "that a diminution of pressure together with a high temperature continued for some time are the conditions necessary for the alteration."

The theory is then proposed that the two minerals are stable in a molten magma only under plutonic conditions, and that the alteration is simply a molecular rearrangement induced by the diminished pressure in volcanic conditions.

The instability of hornblende and biotite as compared with pyroxene is due to their much more complex chemical constitution.

The influence of the chemical composition of the magma is described, but a discussion of it is held to be premature at present.

The disrupting action of the surrounding moving magma in the granular alteration product is touched upon, and it is pointed out that many of the groundmass augites and magnetites must have been derived from altered hornblende or biotite crystals.

It is also suggested that some of the augite-andesites, especially the more acid ones, may owe their augitic character to the alteration and subsequent disintegration of previously existing hornblendes or biotites, in accordance with the views of Von Lasaulx.

Finally, several applications of this idea to the explanation of certain rock occurrences and the succession of volcanic rocks are given.

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